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REDUCING ENVIRONMENTAL IMPACTS • COAL COMBUSTION • CASE STUDY

A life cycle comparison of disposal and beneficial use of coal combustion products in Florida

Part 2: impact assessment of disposal and beneficial use options

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Abstract
Background, aim, and scope Beneficial use of coal combustion products (CCPs) in industrial or construction operations has the potential to minimize environmental and human health impacts that would otherwise be associated with disposal of CCPs in the life cycle of coal used for electricity generation. To assess opportunities for reducing impacts associated with four CCP materials considered in this study, fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) material, this paper reports results of expanding a life cycle inventory of raw material and emissions (part 1 of this series of papers) by performing life cycle impact assessment on five scenarios of CCP management.
Materials and methods SimaPro 5.1 software (PRé Consultants) was used to calculate comparative environmental impacts of all scenarios using CML2001 and Environmental Design of Industrial Products 1997 midpoint impact assessment methods and Heirarchist and Individualist levels of the Eco-indicator 99 end point method. Trends were compared for global and local environmental and human health impact categories of global warming, acidification, smog formation, human toxicity, and ecotoxicity.
Results In each impact category, beneficial use of fly ash, bottom ash, and FGD material resulted in a reduced impact compared to disposal of these materials. The extent to which beneficial use reduced impacts depended on several factors, including the impact category in consideration, the magnitude of potentially avoided impacts associated with producing raw materials that CCPs replace, and the potential impact of CCP disposal methods. Global warming impacts were reduced by the substitution of fly ash for Portland cement in concrete production, as production of Portland cement generates large quantities of CO_2. However, for categories of global warming, smog formation, and acidification, impact reductions from CCP beneficial use are small, less than 6%, as these impacts were attributable, in greater part, to upstream processes of coal mining, transportation, and combustion. Human toxicity and ecotoxicity categories showed larger but more varied reductions, from 0% to 50%, caused by diverting CCPs from landfills and surface impoundments.
Discussion When comparing beneficial use scenarios, the four impact assessment methods used showed similar trends in categories of global warming, acidification, and smog formation. However, results diverged for human toxicity and ecotoxicity categories due to the lack of consensus among methods in classification and characterization of impacts from heavy metal release. Similarly, when assessing sensitivity of these results to changes in assumptions or system boundaries, human toxicity and ecotoxicity categories were most susceptible to change, while other impact categories had more robust results.
Conclusions Impact assessment results showed that beneficial use of CCPs presented opportunities for reduced environmental impacts in the life cycle of coal combusted for electricity generation, as compared to the baseline scenario of 100% CCP disposal, although the impact reductions varied depending on the CCPs used, the ultimate beneficial use, and the impact category in consideration.
Recommendations and perspectives As regulators and electric utilities increasingly consider viability and eco-

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nomics of the use of CCPs in various applications, this study provides a first-basis study of selected beneficial use alternatives. With these initial results, future studies should be directed towards beneficial uses that promise significant economic and environmental savings, such as use of fly ash in concrete, to quantify the currently unknown risk of these applications.

Keywords Beneficial use · Coal combustion · Coal combustion products (CCPs) · Disposal · Impact assessment · Global warming potential

1 Background, aim, and scope

In the preceding paper (Part 1; Babbitt and Lindner 2008), a life cycle inventory (LCI) was conducted to assess raw material and energy requirements and emissions resulting from diverting 50% of coal combustion products (CCPs) from disposal to beneficial use in concrete, soil amendments, road construction materials, blasting grit and roofing granules, and wallboard. Results of this LCI showed promising reductions of certain raw materials and prevention of emissions by diverting half of these materials from landfills or surface impoundments to these six beneficial uses. Here, Part 2 of this study describes the methodology and results of the impact analysis stage of this life cycle assessment (LCA). The relative impacts of each stage considered, coal mining and preparation, coal combustion, CCP disposal, and CCP beneficial use, are compared, and impacts of each beneficial use option are analyzed for their potential improvements or risk to public and environmental health.

2 Materials and methods

Scope, goals, system boundaries, and results of the inventory of material and energy inputs and emissions were previously presented (Babbitt and Lindner 2004, 2008). These methods are summarized below and extended here to include the LCA impact assessment stage.

2.1 LCA background

The goals of this LCA were to extend the previous life cycle inventory of various CCP beneficial uses to examine opportunities in the CCP life cycle to prevent or minimize environmental or human health impacts. The ultimate objective was to aid CCP generators and state regulators in evaluating CCP management options to minimize impact to human and environmental health. The scope included coal mining and preparation, coal combustion, CCP disposal, and CCP beneficial use. This assessment was limited to Florida electric utilities, as this project was funded by the Florida Department of Environmental Protection and involved collaboration with the Florida Electric Power Coordinating Group, a Florida consortium of electric utilities.

The functional unit was "per 1,000 kg of coal combusted," and the system represented typical pulverized coal-fired power generation in Florida, although this process is common to many US power plants (Spath et al. 1999). System boundaries included natural resource extraction and preparation, materials and chemicals production, transportation, infrastructure and capital goods, energy consumption, and emissions to air, water, and land. Based on a previous LCI (Babbitt and Lindner 2004) and Part 1 of this study (Babbitt and Lindner 2008), it was assumed that 50% (108 kg) of CCPs generated from combusting 1,000 kg of coal is equally divided for disposal in a landfill or surface impoundment and the remaining 50% (108 kg) is diverted to a beneficial application as a replacement for virgin raw material.

Because the CCP beneficial use stage involves substitution of CCPs for other materials, system boundaries for beneficial use scenarios were expanded to include avoided upstream processes (mining, refining, transportation) for materials replaced by CCPs since they have similar characteristics and performance (Ekvall and Finnveden 2001). Use and disposal of products made with CCPs were not considered, as it was assumed that these would be unchanged by the CCPs, an assumption necessitated by a lack of available data on regional and temporal performance and environmental impacts of products made with CCPs.

2.2 Life cycle scenarios

Part 1 of this series (Babbitt and Lindner 2008) provided two scenarios of CCP management: 100% disposal of all CCPs in on-site landfills and surface impoundments or disposal of 50% of the CCPs and beneficial use of the remaining 50%. This LCA expands those scenarios (baseline and scenario D, below) by also considering cases of 50% beneficial use of each type of CCP (A–C):

- Baseline scenario: 100% disposal of CCPs in landfills (50%) and surface impoundments (50%)
- Scenario A: 50% beneficial use–50% disposal of fly ash and bottom ash, 100% disposal of remaining CCPs
- Scenario B: 50% beneficial use–50% disposal of boiler slag, 100% disposal of remaining CCPs
- Scenario C: 50% beneficial use–50% disposal of FGD material, 100% disposal of remaining CCPs

– Scenario D: 50% beneficial use–50% disposal of all CCPs generated

Expanding the scenarios in this manner allows comparison of environmental savings opportunities relative to each type of CCP material and specific industrial applications in which it can be used. Beneficial uses considered for each type of CCP are the same as those considered in Part 1 of this series (Babbitt and Lindner 2008), and it was assumed that, for every mass unit of CCP used in a beneficial application, the traditional, virgin raw material required would be decreased by the same amount. All beneficial uses were assumed to occur within 50 miles of the CCP-generating utility, and CCP transportation was included in the system boundaries.

2.3 Life cycle impact assessment methods

Three impact assessment methods were used: Eco-indicator 99, a damage-based endpoint method, and Environmental Design of Industrial Products 1997 (EDIP97) and CML2001 (Goedkoop and Spriensma 2001; Centrum Voor Milieukunde Leiden 2001; Guinée and Heijungs 1993; Wenzel et al. 1997), problem-based, midpoint methods. It has been shown that applying these methods to the same inventory data can result in very different outcomes in each impact category (Dreyer et al. 2003). However, the goal of this LCA was not to calculate absolute impact quantities but to compare trends in CCP management scenarios. Heuristic (H) and individualist (I) levels of Eco-indicator 99 were used to address uncertainty in the time period in which emissions are expected to create environmental and human health impacts. In the CCP disposal stage, release of heavy metals from unlined disposal facilities is expected to create impacts in human toxicity and ecotoxicity categories. However, it is unknown how long these impacts will persist or if their severity will change over time. The heuristic level of Eco-indicator 99 is used to incorporate a long time perspective and to include substances generally recognized for their potential impacts (Goedkoop and Spriensma 2001). The individualist level uses a shorter time horizon (<100 years) and includes only substances with proven impacts (Goedkoop and Spriensma 2001). Because impacts associated with CCP beneficial use are currently unknown or not quantified, a more conservative approach to modeling impacts from disposal is appropriate, as to not overly exaggerate the difference between these two management options.

Impact categories selected were global warming, acidification, smog formation, ecotoxicity, and human toxicity. These categories were selected based on their relevance to the major emissions expected from CCP generation and management, especially air emissions produced by coal combustion and metals released from CCP disposal (Babbitt and Lindner 2004, 2008). In addition, environmental and human health impacts from the coal combustion life cycle are expected to occur on global and local scales, and the impacts chosen represent both geographical perspectives. For most categories, impacts are aggregated in similar manners, but EDIP97 separates human toxicity into impacts to air, water, and land, and, thus, the separate impacts were summed to be comparable with other methods. Similarly, EDIP97 differentiates between acute and chronic human toxicity, while CML2001 accounts for only chronic toxicity and Eco-indicator 99 makes no distinction. Therefore, only chronic ecotoxicity values were used for EDIP97 (Dreyer et al. 2003), and values for soil and water were summed to obtain a total ecotoxicity impact.

The products of all inventoried emissions and the respective impact factors for each impact category were summed to obtain the total contribution of the life cycle to that environmental impact. A relative percentage impact was determined, using the baseline scenario (100% CCP disposal) as the reference to compare all other options. This approach allows direct comparison of trends among categories and methods and eliminates difficulties of using different units in each category or method. In addition, the fold differences for each beneficial use scenario were calculated to assess if reduced impact from CCP beneficial use was attributable more to diverting the CCP from a disposal facility or more to replacing a traditional raw material and avoiding extraction and production impacts that would otherwise be associated with that raw material. Fold differences were calculated as [total impact scenario $n-$ total impact baseline scenario]/total impact baseline scenario, for all scenarios, A–D.

Because the goal of this work was to provide a comparative analysis of CCP beneficial use options rather than calculate absolute environmental impacts, normalization and valuation were not included in the analysis. Results of this LCA will be used by a variety of stakeholders, including academia, electric utilities, and regulators, whose interests were best served by presenting unweighted results and allowing each party to draw conclusions based on their established values and priorities.

2.4 Sensitivity analysis

Interpretation and use of this study's results are somewhat limited by assumptions made for the system boundaries, in data collected from primary and secondary sources, and from impact assessment methods used. A sensitivity analysis was performed to relate the effect of variations in the system with modeled impact results. To this end, four

cases were considered, again using the baseline of 100% disposal of CCPs to compare results:

– Case 1: 100% disposal of CCPs in landfills only
– Case 2: 100% beneficial use of all CCPs within a 50-mile distance
– Case 3: 100% beneficial use of all CCPs within a 100-mile distance
– Case 4: 100% beneficial use of all CCPs within a 500-mile distance

Case 1 was used to determine the effect of assumptions of disposal options (the baseline scenario splits CCPs equally in landfill and surface impoundment). However, utility data collected showed that landfills were often used for long-term CCP disposal in Florida, while surface impoundments were used over a shorter time period. Cases 2–4 address transportation assumptions, as utilities report that costs of transporting CCPs beyond a 50-mile radius offset profits from CCP sales. This comparison was used to determine if the distance similarly limits beneficial use from an environmental perspective and if the increased beneficial use (from 50% to 100%) would offset this limitation. Because the same baseline scenario was used for beneficial use comparisons and sensitivity analysis, the results can be compared directly within each impact assessment method used.

3 Results and discussion

Results of impact assessment for the baseline scenario, using three impact assessment methods, are presented in Table 1. These results are shown both as total impacts for each stage and the entire life cycle and as the relative percent that each stage contributes to the total impact. Impacts of each beneficial use scenario, relative to the baseline scenario, are shown in Fig. 1, where each value represents the relative beneficial use impact for each scenario considered divided by the total impact of the baseline scenario (the total values in Table 1). The fold differences for each beneficial use scenario are shown in Table 2, and these results include the total fold difference as well as relative contributions to the difference that result from diverting materials from disposal or from replacing traditional raw materials and avoiding their production impacts. Sensitivity of the LCA to assumptions about CCP disposal and transportation to beneficial uses is shown in Fig. 2, where each value represents the change in total life cycle impacts as compared to the baseline scenario (100% CCP disposal), averaged over all four impact methods used, with error bars representing the standard deviation among results of each of the four methods used.

3.1 Comparison of CCP management scenarios for each impact category

3.1.1 Global warming

All four impact assessment methods show similar trends in the impact category of global warming potential. In the baseline scenario, coal mining and transportation contributes between 30% and 34% to global warming potential, while coal combustion contributes about 65–69% to this impact (see Table 1). Although CCP disposal for the baseline only causes 0.2% of the total global warming potential for the baseline, a reduction in impact was calculated when examining the beneficial use of fly ash and bottom ash (2.3% reduction), FGD material (2.3–2.4% reduction), and all CCPs (4.5–4.6% reduction; see Fig. 1, 1-1). Because CCP disposal is not a major source of greenhouse gases, the reductions were due to replacing traditional raw materials by CCPs, rather than diverting CCPs from disposal (see Table 2). Global warming impacts prevented by beneficial use largely are attributed to substitution of fly ash for Portland cement in concrete production, which reduces CO_2 emissions from the Portland cement process and replacement of natural gypsum with FGD gypsum in wallboard production, which reduces CO_2 emissions that would be generated from energy use in mining and processing natural gypsum. Boiler slag use does not affect global warming impacts significantly, as materials it replaces in blasting grit and asphalt roofing granules (glass, sand, and gravel) would not otherwise create high greenhouse gas emissions. Consistency in results among all impact assessment methods is not surprising, given the consensus on classification of greenhouse gases and quantification of their impacts. For this impact category, use of different impact methodologies does not hinder comparison of LCA trends among different scenarios.

3.1.2 Acidification

Results from all four methods indicate that coal mining and coal combustion have the highest impact to acidification of aquatic systems, as shown in Table 1. Acidification impacts are associated with acid mine drainage, waste water from coal cleaning, and production of sulfur dioxide and nitrogen oxides during coal combustion. Environmental impacts created by CCP disposal are one to three orders of magnitude less than from the first two stages of this LCA (see Table 1). However, CCP beneficial use does present an opportunity for small environmental savings from fly ash and FGD material use (see Fig. 1), and, where reductions are observed, they are attributed to replacement of traditional raw materials, particularly Portland cement and natural gypsum, rather than decreasing CCPs sent to a landfill or surface impoundment (see Table 2).Use of boiler

Table 1 Total and percent contributions from each life cycle stage to total life cycle impacts of the baseline CCP generation and management scenarios

Method	Impact category	Unit	Contribution from each life cycle stage to total impact — Results as total impact (percent of total): Coal mining and preparation	Coal combustion	100% disposal of all CCPs	Total impact
Eco-indicator99(I)	GWP	DALY	8.3E−05 (31.2)	1.8E−04 (68.6)	5.9E−07 (0.2)	2.7E−04
	ACP	PDF*m^2 year	1.3E+01 (47.1)	1.5E+01 (52.5)	1.2E−01 (0.4)	2.8E+01
	HTP	DALY	5.8E−05 (10.7)	6.7E−06 (1.2)	4.8E−04 (88.1)	5.4E−04
	ETP	PAF*m^2 year	4.7E+01 (0.7)	4.0E+01 (0.6)	6.7E+03 (98.7)	6.7E+03
Eco-indicator99(H)	GWP	DALY	8.6E−05 (30.8)	1.9E−04 (69.0)	6.2E−07 (0.2)	2.8E−04
	ACP	PDF*m^2 year	1.3E+01 (47.1)	1.5E+01 (52.5)	1.2E−01 (0.4)	2.8E+01
	HTP	DALY	1.3E−04 (2.8)	4.1E−05 (0.9)	4.4E−03 (96.3)	4.6E−03
	ETP	PAF*m^2 year	2.5E+02 (0.6)	2.6E+02 (0.6)	4.2E+04 (98.8)	4.2E+04
EDIP97	GWP	kg CO_2 eq	4.7E+02 (33.9)	9.2E+02 (65.9)	3.1E+00 (0.2)	1.4E+03
	ACP	kg SO_2 eq	2.7E+00 (32.1)	5.6E+00 (67.6)	2.3E−02 (0.3)	8.3E+00
	SFP	kg C_2H_2 eq	8.4E−02 (90.8)	7.0E−03 (7.5)	1.5E−03 (1.7%)	9.3E−02
	HTP	m^3/g	1.6E+08 (73.4)	3.4E+07 (15.7)	2.4E+07 (10.9)	2.2E+08
	ETP	m^3/g	1.0E+06 (93.0)	7.8E+03 (0.7)	6.9E+04 (6.3)	1.1E+06
CML2001	GWP	kg CO_2 eq	4.3E+02 (31.6)	9.2E+02 (68.2)	3.0E+00 (0.2)	1.3E+03
	ACP	kg SO_2 eq	2.0E+00 (31.5)	4.3E+00 (68.2)	2.0E−02 (0.3)	6.3E+00
	SFP	kg C_2H_2 eq	1.4E−01 (43.0)	1.8E−01 (56.4)	2.1E−03 (0.7)	3.1E−01
	HTP	kg 1,4-DB eq	3.9E+02 (15.0)	1.5E+02 (5.8)	2.0E+03 (79.3)	2.6E+03
	ETPS	kg 1,4-DB eq	3.5E+05 (9.3)	3.9E+05 (10.4)	3.0E+06 (80.3)	3.8E+06

GWP Global warming potential, *ACP* acidification potential, *SFP* smog formation potential, *HTP* human toxicity potential, *ETP* ecotoxicity potential, *DALY* disability adjusted life years, *PAF*m^2 year* potentially affected fraction of species, *PDF*m^2 year* potentially disappeared fraction of species, *kg CO_2 eq* kilogram carbon dioxide equivalents, *kg SO_2 eq* kilogram sulfur dioxide equivalents, *kg C_{22} eq* kilogram ethylene equivalents, *m^3/g* cubic meters compartment dilution required per gram of substance to negate any toxic effects, *kg 1,4-DB eq* kilograms 1,4 dichlorobenzene equivalents

slag, however, actually causes a slight increase in acidification, due to emissions generated from wet handling and transportation of this material. Acidification impacts for the different beneficial uses show similar trends when compared across the four impact methods, as shown in Fig. 1, 1-3. There is a slight discrepancy among the methods when comparing absolute impact values for FGD material beneficial use, which causes a greater reduction in emissions of NO_X than in emissions of SO_2 as compared to 100% FGD disposal. Both Eco-indicator 99 methods weigh NO_X greater than SO_2, whereas the opposite is true for EDIP 97 and CML2001. However, comparing results calculated by all four methods, FGD beneficial use shows a slightly larger reduction in acidification than does beneficial use of fly ash and bottom ash. Beneficial use of all CCPs presents roughly a 3–5% overall reduction in acidification impacts compared to 100% disposal of these materials.

3.1.3 Photochemical smog formation

EDIP 97 and CML2001 methods include a photochemical smog formation impact category. Results indicate that this impact is mostly caused by NO_X emissions from coal mining and combustion and by volatile organic carbon emissions from coal mining and transportation (see Table 1). CCP beneficial use shows potential to reduce smog formation impacts, mostly attributed to beneficial use of fly ash, bottom ash, and FGD material (see Fig. 1, Table 2). Impact reduction trends between these two methods show strong agreement (see Fig. 1, 1-4**)**, although reductions calculated by the EDIP97 method are slightly higher.

3.1.4 Carcinogens and human toxicity

In three impact assessment methods, CCP disposal contributes the greatest amount to carcinogen and human toxicity impact (see Table 1), although results from the EDIP97 method show a slightly greater impact to human toxicity from coal mining, due to metals released from coal tailings and mine drainage. CCP disposal impacts are high because of the risk posed by potential release of metals from unlined landfills and surface impoundments. In Florida, most active and closed storage and disposal facilities are unlined (Babbitt and Lindner 2004). Toxicity reductions would be expected in beneficial uses such as substitution of Portland cement by fly ash in

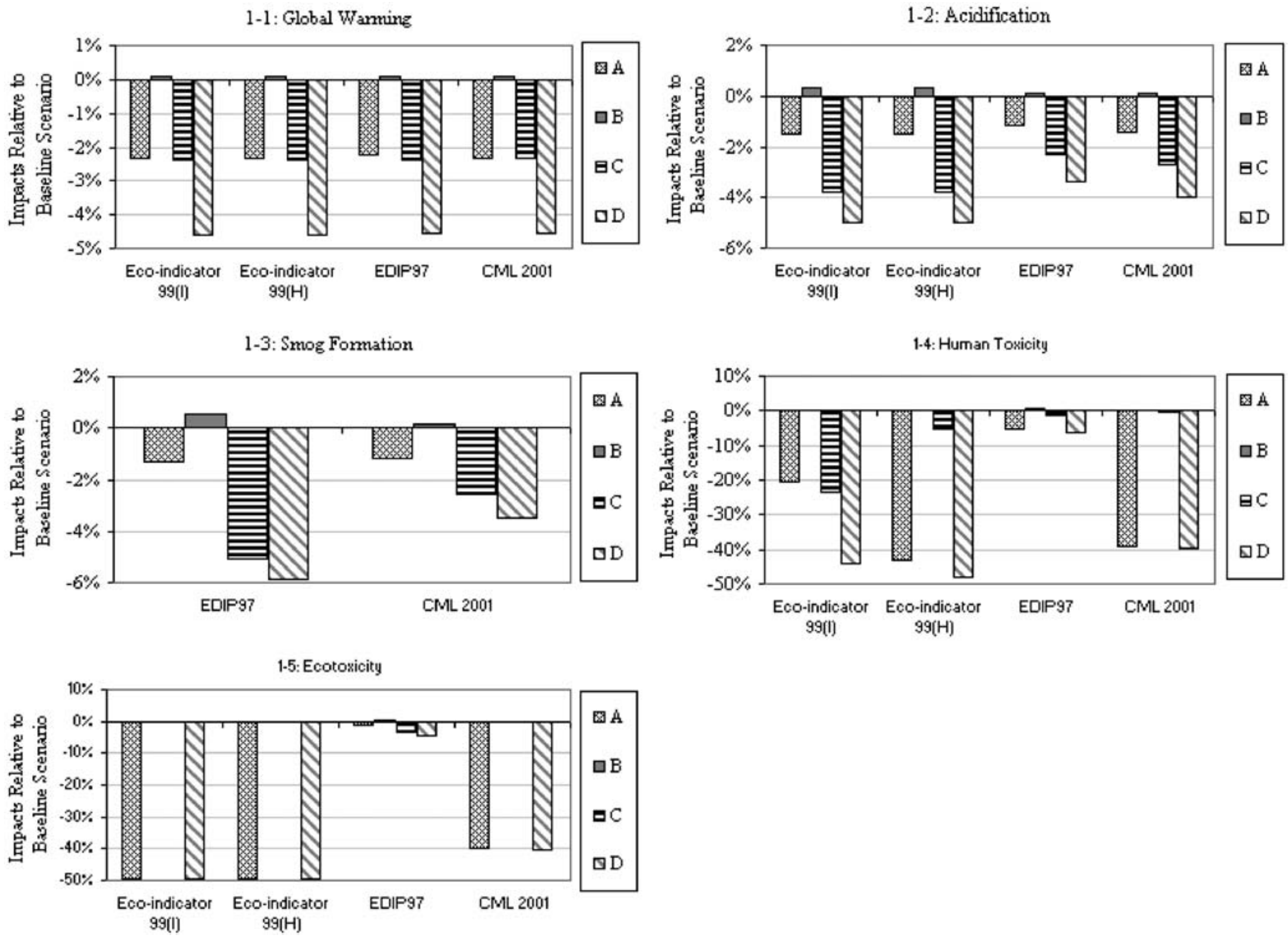

Fig. 1 Comparison of four impact assessment methods for determining trends in environmental impacts of CCP management scenarios. The baseline scenario was set as 0%, and all other CCP management scenarios (*A–D*) were represented as percentage change in impact relative to the baseline. Negative values indicate the avoidance of an impact due to beneficial use rather than disposal of a CCP

concrete, where metals contained in the CCP are bound in a cementitious matrix, as opposed to direct application to land for soil amendment (e.g., Dienhart et al. 1998; Alcordo and Rechcigl 1995; Punshon et al. 1999; Alva et al. 1999). Figure 1 shows that beneficial use of fly ash, bottom ash, FGD material, and all CCPs (scenarios A, C, D) can reduce human toxicity impacts, but it is important to note that these reductions are due to diverting CCPs from disposal, rather than substituting CCPs for raw materials (see Table 2). Therefore, potential to reduce impacts from metal emissions would be less if the CCPs were used in applications where metals can be released into the environment. In this case, the life cycle impact would not be reduced but only removed in time and space from the original disposal point. Since data about metals in common CCPs applications are incomplete, caution must be taken in interpreting these results.

Despite agreement among methods that CCP disposal has high human toxicity impact (see Table 1), comparisons are hindered by differences among the methods in classifying and characterizing the carcinogenicity of metals. Eco-indicator 99(H) includes known and suspected carcinogens, and, therefore, results in the highest estimation of impacts reduced by diverting CCPs from disposal to beneficial use (see Fig. 1, 1-5). On the other hand, EDIP97 shows a very conservative estimate of impact reduction, as most impacts in this method are associated with upstream CCP generation, not CCP disposal. Although comparisons of trends among the scenarios is difficult for this impact, Fig. 1, 1-5, shows that even for the most conservative estimate, beneficial use of fly ash, bottom ash, and FGD material show some benefit compared to 100% CCP disposal. However, lack of consistency in the magnitude of these results supports previous work (Dreyer et al. 2003) that showed comparisons among methods are not possible when impact methods vary widely in inclusion or exclusion of materials or in calculations of impact factors for the materials.

Table 2 Fold differences between the baseline scenario and each of the four beneficial use scenarios

Method	Impact category	Fold differences[a] from baseline			
		Total and relative contributions from reduced disposal and beneficial use[b]			
		Scenario A: fly ash and bottom ash	Scenario B: boiler slag	Scenario C: FGD material	Scenario D: all CCPs
Eco-indicator99(I)	GWP	−10.5 (−0.2/−10.3)	0.5 (−0.01/0.5)	−10.7 (−0.3/−10.4)	−20.7 (−0.5/−20.2)
	ACP	−3.6 (−0.2/−3.4)	0.7 (−0.01/0.7)	−9.1 (−0.3/−8.8)	−12.0 (−0.5/−11.5)
	HTP	−0.2 (−0.2/0.0)	0.0 (0.0/0.0)	−0.3 (−0.3/0.0)	−0.5 (−0.5/0.0)
	ETP	−0.5 (−0.5/0.0)	0.0 (0.0/0.0)	0.0 (0.0/0.0)	−0.5 (−0.5/0.0)
Eco-indicator99(H)	GWP	−10.5 (−0.2/−10.3)	0.5 (−0.01/0.5)	−10.6 (−0.3/−10.3)	−20.6 (−0.5/−20.1)
	ACP	−3.6 (−0.2/−3.4)	0.7 (−0.01/0.7)	−9.1 (−0.3/−8.8)	−12.0 (−0.5/−11.5)
	HTP	−0.4 (−0.4/0.0)	0.0 (0.0/0.0)	−0.1 (−0.1/0.0)	−0.5 (−0.5/0.0)
	ETP	−0.5 (−0.5/0.0)	0.0 (0.0/0.0)	0.0 (0.0/0.0)	−0.5 (−0.5/0.0)
EDIP97	GWP	−10.2 (−0.2/−10.0)	0.5 (−0.01/0.5)	−10.8 (−0.3/−10.5)	−20.5 (−0.5/−20.0)
	ACP	−4.3 (−0.2/−4.1)	0.5 (−0.01/0.5)	−8.6 (−0.3/−8.3)	−12.4 (−0.5/−11.9)
	SFP	−0.8 (−0.2/−0.6)	0.3 (−0.01/0.3)	−3.1 (−0.3/−2.8)	−3.5 (−0.5/−3.0)
	HTP	−0.5 (−0.5/0.0)	0.0 (0.0/0.0)	−0.1 (0.0/−0.1)	−0.6 (−0.5/−0.1)
	ETP	−0.2 (−0.2/0.0)	0.0 (0.0/0.0)	−0.5 (−0.3/−0.2)	−0.7 (−0.5/−0.2)
CML2001	GWP	−10.4 (−0.2/−10.2)	0.5 (−0.01/0.5)	−10.6 (−0.3/−10.3)	−20.5 (−0.5/−20.0)
	ACP	−4.6 (−0.2/−4.4)	0.5 (−0.01/0.5)	−8.5 (−0.3/−8.2)	−12.7 (−0.5/−12.2)
	SFP	−1.8 (−0.2/−1.5)	0.3 (−0.01/0.3)	−3.8 (−0.3/−3.5)	−5.3 (−0.5/−4.8)
	HTP	−0.5 (−0.5/0.0)	0.0 (0.0/0.0)	0.0 (0.0/0.0)	−0.5 (−0.5/0.0)
	ETP	−0.5 (−0.5/0.0)	0.0 (0.0/0.0)	0.0 (0.0/0.0)	−0.5 (−0.5/0.0)

GWP Global warming potential, *ACP* acidification potential, *SFP* smog formation potential, *HTP* human toxicity potential, *ETP* ecotoxicity potential

[a] Fold difference is calculated as relative change from the total impact of the baseline scenario to the total impact of the CCP management strategy for each scenario investigated (e.g., fold difference=[total impact scenario n−total impact baseline scenario]/total impact baseline scenario for all scenarios A–D)

[b] Results are expressed as total fold difference (fold difference due to reduced CCP disposal/fold difference due to material replacement in beneficial use)

3.1.5 Ecotoxicity

Ecotoxicity impacts followed similar trends as human toxicity impacts. Eco-indicator 99 and the CML2001 methods resulted in the conclusion that ecotoxicity impacts are created by CCP disposal at levels one to two orders of magnitude greater than impacts created by coal mining or combustion (see Table 1), while the EDIP97 method, on the other hand, showed results that coal mining and preparation contributed the greatest degree to ecotoxicity (see Table 1).

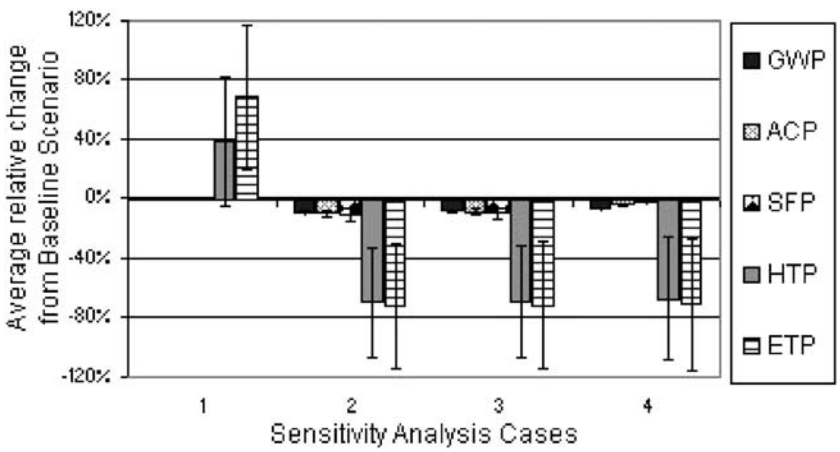

Fig. 2 Sensitivity analysis of life cycle variables. Each of the sensitivity analyses (cases *1–4*) was compared to the baseline scenario (set to 0%) and results were represented as a percent change in impact compared to the baseline. *GWP* global warming potential; *ACP* acidification potential; *SFP* smog formation potential; *HTP* human toxicity potential; *ETP* ecotoxicity potential

Where both Eco-indicator 99 methods predict that ecotoxicity is attributed exclusively to CCP disposal, due to potential heavy metal emissions, the EDIP 97 method indicates that metals emissions in combustion flue gas and uncontrolled runoff from coal piles and mine tailings play a greater role in ecotoxicity impacts. Regardless of the method, it is expected that diverting CCPs, particularly fly ash and bottom ash (see Fig. 1), from disposal facilities to beneficial uses can possibly reduce the total impact calculated for this category.

Eco-indicator 99(I) and (H) and CML2001 methods all show a 40–50% reduction in ecotoxicity impacts from fly ash and bottom ash beneficial use (Figs. 1 and 2). Because the EDIP97 method attributes more ecotoxicity impact to coal mining than to CCP disposal, the reduction from CCP beneficial use is much lower, approximately 1.1% for fly ash and bottom ash and 3.3% for FGD material. Differences among the models are due primarily to the relative impact factor values used for metals emitted to soil. The Eco-indicator 99(I) and (H) and CML2001 methods place higher values on metals such as copper, arsenic, and lead, all of which are emitted from CCP disposal facilities (Babbitt and Lindner 2008) and, thus, reduced when CCPs are diverted. On the other hand, EDIP97 more heavily weigh metals such as cobalt, molybdenum, and mercury, which are emitted in lower quantities from CCP disposal facilities, compared to other life cycle stages. However, scenarios of fly ash, bottom ash, and FGD material beneficial use all show some reductions in ecotoxicity impacts, indicating an opportunity for environmental savings in the coal combustion life cycle. It is important to note that these reductions are almost completely due to diverting material from disposal, rather than substituting the CCP for another raw material in a beneficial use (see Table 2). Again, conclusions based on these results are limited by unknowns surrounding the ultimate fate of metals in CCPs used in beneficial use applications.

3.2 Sensitivity analysis

Results of sensitivity analysis on system boundaries and assumptions are shown in Fig. 2, where changes assessed using all four methods are shown as relative values compared to the baseline 100% CCP disposal and discussed in greater detail below

3.2.1 Disposal of 100% of all CCPs in landfills only

The survey of Florida utilities revealed that about half of CCPs generated were placed in landfills and half in surface impoundments (Babbitt and Lindner 2004). However, it was also noted that, in many instances, CCPs were eventually moved to landfills for permanent disposal or put in impoundments only until they were sold for beneficial use. To determine the effect of disposal method on life cycle results, case 1 proposed that 100% of all CCPs are disposed in landfills only. As shown in Fig. 2, impacts to global warming, acidification, and smog formation are not affected by this assumption because these impacts are related more to processes in coal mining and combustion. However, increasing the amount of CCPs landfilled increases human toxicity and ecotoxicity impacts by an average of 40% and 70%, respectively. However, the variation in this increase among the four methods used is as high as the change in impact itself (see Fig. 2), indicating that these results are very sensitive to the impact assessment method used and, also, to the assumption of the proportion of material divided between landfill and impoundment. Based on these variations, it is evident that the CCP disposal impact results of Fig. 1 and Table 1 may not be applicable for every utility and should be interpreted with consideration to specific disposal practices at the facility of interest.

3.2.2 Increase of CCP beneficial use to 100% in an increasing radius from the electric utility

One of the surveyed utilities actually sells almost 100% of all CCPs generated through aggressive marketing and colocation of a beneficial use market adjacent to the utility (Babbitt and Lindner 2004), although this is far from being the norm in the US. Many utilities report they are limited by the costs of transporting CCPs over distances greater than about 50 miles (Babbitt and Lindner 2004), which is especially problematic when CCPs are replacing readily available raw materials, such as gravel and rock in road base or aggregate. Therefore, this analysis sought to determine the additional environmental savings accrued by beneficially using 100% of CCPs generated use within a 50-mile (case 2), 100-mile (case 3), or 500-mile (case 4) radius. Studying these options helps assess if distance is as environmentally prohibitive to additional beneficial use as it is costly to the utilities. Figure 2 shows that for cases 2, 3, and 4, increasing beneficial use to 100% does indeed reduce impacts to a greater extent than previously shown for 50% use. Relative reductions show variation among different impact assessment methods used and different impact categories, especially impacts associated with the added transportation requirement. Most variability is again seen for human toxicity and ecotoxicity, as previously described. However, regardless of this variability, all methods show that impacts in every category are reduced by increasing the amount of CCPs diverted from disposal and beneficially used (see Fig. 2). Therefore, utilities could possibly expand CCPs markets, increase the current 50% beneficial use average, and realize greater environmental

benefits by considering CCP sale beyond the current 50-mile limit. However, the cost barrier to increasing transportation of CCPs must be overcome.

4 Conclusions

Impact assessment using Eco-indicator 99(I), Eco-indicator 99(H), EDIP97, and CML2001 methods showed that beneficial use of CCPs presented opportunities for reduced environmental impacts in the life cycle of coal used for electricity generation, as compared to a baseline of 100% CCP disposal. In the categories of climate change, acidification, and photochemical smog formation, 50% CCP beneficial use resulted in avoidance of impacts that would otherwise be created when certain virgin raw materials were used in applications such as concrete production and gypsum wallboard manufacture. Conversely, because the CCP disposal stage contributed heavily to human toxicity and ecotoxicity, beneficial use would reduce those impacts simply by diverting CCPs from disposal rather from substituting a CCP for another raw material in a beneficial application. In addition, by comparing relative environmental impact reductions associated with beneficial uses to a baseline scenario, rather than using absolute impact scores, it was possible to use assessment methods with very different scopes, impact factors, and units. The highest variability in impact reduction in scenarios A–D, compared to the baseline scenario, was observed for human toxicity and ecotoxicity. Despite different approaches used by these methods in weighting metals, results led to a consistent conclusion that reducing environmental and human health impacts was possible through CCP beneficial use. The ability to use vastly different methods and still obtain the same general trends shows robustness in conclusions drawn for this life cycle case study.

5 Recommendations and perspectives

At a time when the utility industry anticipates changes in the amounts and quality of CCPs produced, as a result of increased demand in coal combustion and future air regulations, this study emphasizes potential environmental savings of CCP beneficial use applications. This life cycle model, while sensitive to system boundaries considered, can be expanded to study individual beneficial uses, specific end-of-life challenges, and performance and environmental effects of products made using CCPs.

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References

Alcordo IS, Rechcigl JE (1995) Phosphogypsum and other by-product gypsums. In: Rechcigl JE (ed) Soil amendments and environmental quality. CRC, Boca Raton, p 365

Alva AK, Zhu B, Hostler HK, Obreza TA (1999) Citrus tree growth and fruit production response to flue-gas desulfurization gypsum amendment in sandy soils. In: Sajwan KS, Alva AK, Keefer RF (eds) Biogeochemistry of trace elements in coal and coal combustion byproducts. Kluwer Academic/Plenum Publishers, New York

Babbitt CW, Lindner AS (2004) A life cycle inventory of coal used for electricity production in Florida. J Cleaner Prod 13(9):903–912

Babbitt CW, Lindner AS (2008) A life cycle comparison of disposal and beneficial use of coal combustion products in Florida. Part 1: methodology and input and emissions inventory. Int J Life Cycle Assess 13(3):202–211

Centrum Voor Milieukunde Leiden (CML) (2001) Part 3: scientific background. In: Guinée J et al. (eds) Life cycle assessment: an operational guide to the ISO standards. A Report for the Ministries of Housing, Spatial Planning and the Environment, Economic Affairs, Transport, Public Works and Water Management, Agriculture, Nature Management and Fisheries, CML, Leiden University, The Netherlands, http://www.leidenuniv.nl.interfac/cml/ssp/projects/lca2/lca2.html. Accessed 23 May 2004

Dienhart GJ, Stewart BR, Tyson SS (eds) (1998) Coal ash: innovative applications of coal combustion products. American Coal Ash Association, Alexandria

Dreyer LC, Niemann AL, Hauschild MZ (2003) Comparison of three different LCIA methods: EDIP97, CML2001, and Eco-indicator 99—does it matter which one you choose? Int J Life Cycle Assess 8(4):191–200

Ekvall T, Finnveden G (2001) Allocation in ISO 14041—a critical review. J Clean Prod 9:197–208

Goedkoop M, Spriensma R (2001) The Eco-indicator 99: a damage-oriented method for life cycle assessment. PRé Consultants, Amersfoort

Guinée J, Heijungs R (1993) A proposal for the classification of toxic substances within the framework of life cycle assessment of products. Chemosphere 26:1925–1944

Punshon T, Know AS, Adriano DC, Seaman JC, Weber JT (1999) Flue gas desulfurization (FGD) residue: potential applications and environmental issues. In: Sajwan KS, Alva AK, Keefer RF (eds) Biogeochemistry of trace elements in coal and coal combustion byproducts. Kluwer Academic/Plenum, New York

Spath PL, Mann MK, Kerr DR (1999) Life cycle assessment of coal-fired power production. National Renewable Energy Laboratory, Goldon

Wenzel H, Hauschild MZ, Alting L (1997) Environmental assessment of products. Vol. 1—methodology, tools, techniques and case studies. Chapman & Hall/Kluwer Academic Publishers, Hingham, p 544